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CLOUD PROPERTIES FROM SATELLITE INFRARED AND VISIBLE MEASUREMENTS

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1. INTRODUCTION

1.1 Objectives

Exposed materials on high speed vehicles such as supersonic aircraft and rockets can be substantially eroded by the water or ice particles of clouds. Engineering tests of various materials suggest that the mass density of hydrometeors is the most significant meteorological parameter related to erosion. Cloud mass density however is not measured routinely, and it is difficult to model the radiative properties observed by satellites for ice particles with varying shape, size and number concentration. Therefore, radiation data from satellites have been compared to simultaneous cloud measurements by aircraft underflights. A variety of cloud conditions including nimbostratus, stratocumulus and cirrus have been sampled over mid-latitudes of the USA during winter and spring months and analyzed with the infrared (IR) and visible measurements from NOAA satellites. Radiances at 12-15 μm measured by Vertical Temperature Profile Radiometer (VTPR) instruments are combined with known temperature profiles in order to estimate cloud altitude and infrared (IR) transmissivity. Broadband visible and IR window measurements taken by the Scanning Radiometers on board the same satellites are empirically related to total cloud thickness and mass.

1.2 Related Studies

Satellite measurements of radiance at 8 to 12 μm are frequently used to estimate cloud altitude. The measured radiances are converted to the temperatures of a blackbody, weighted over the spectral interval of the sensor, and along with a temperature altitude relation, used to estimate cloud altitude. The altitudes are often underestimated when satellites view cirriform clouds. Both theory and experiment have shown that cirriform clouds may be semitransparent to terrestrial radiation. Jacobowitz (1970) found that measurements of upwelling radiation in the 15 μm band of CO_2 could be used to estimate the optical depth of cirriform clouds, provided that the vertical profile of atmospheric temperature was known and that cirriform clouds were the only clouds viewed by the satellite. Bunting and Conover (1974) extended the use of VTPR radiances to estimate both cloud altitude and transmissivity. Results of application of this model to field measurements of cirriform and other clouds are presented in Section 3.

Theoretical studies have simulated the radiative properties of clouds. Extensive calculations have been made for many spectral regions, primarily using Mie theory to calculate scattering, absorption, and emission for spherical cloud particles. Summaries of results are available (Deirmendjian, 1969), (Mosher, 1974), and the form of these results is instructive. For instance, calculations for IR show that water clouds are effective absorbers of infrared radiation while thin cirrus clouds are semitransparent. Calculations in the visible by Twomey, Jacobowitz, and Howell (1967) and others show that cloud reflectance increases with increasing cloud depth approaching an asymptotic limit at less than 100 percent reflectance. In addition, satellite measurements of reflected sunlight have been related to observed cloud thickness by Reynolds and Vonder Haar (1973), Griffith and Woodley (1973), and others, and they conclude that the thickest clouds appear the brightest.

Although calculations of sunlight scattered by clouds suggest the general form of relationships between cloud mass and thickness and reflectivity in the visible, direct observations were necessary due to serious limitations in the calculations. Scattering models generally use a uniform distribution of cloud particles throughout the cloud, and vary the thickness of the cloud. This assumption is probably reasonable for thin clouds such as stratocumulus or cirrostratus, but is not consistent with cloud particle measurements in deep, precipitating clouds. These same models also assume that all particles have a simple shape, spherical or cylindrical (Liou, 1972). This assumption is probably valid for some thin clouds, but is incorrect for deep clouds which may contain ice fragments, aggregates, graupel, rimed particles, dendrites or other irregularly shaped particles. These uncertainties of shape make it difficult to calculate phase functions for single scattering, leaving aside the enormous additional complications of multiple scattering. Near cloud edges, consideration must be given to scattering out the sides of the cloud (McKee and Cox, 1975). The scattering models must also account for a small amount of absorption of visible light by cloud particles and gases, and the reflecting properties of the underlying surface must be included. The most serious difficulty in a theoretical approach is the need to guess at the particle size distribution of the cloud and consider major variations with altitude.

2. OBSERVATIONS

2.1 Satellite Data

The satellite instruments used in this study are the Vertical Temperature Profile Radiometers (VTPR) and Scanning Radiometers (SR) on board the NOAA ITOS series of satellites.

The VTPR instruments measure radiance for narrow spectral intervals in the 12-15 μm absorption band of CO_2. The VTPR radiances of bands 4, 5, 6, and 8 are used here. Spectral characteristics of these bands are given in Table 1. The horizontal resolution of VTPR measurements is about 70x70 km at the satellite subpoint. The instrument is described in more detail by McMillin et al (1973).

Table 1

Characteristics of typical VTPR bands

Band Number	4	5	6	8
Wavenumber (cm^{-1})	708.7	723.6	746.7	833.7
Wavelength (μm)	14.1	13.8	13.4	12.0
Peak of Typical Weighting Function (mb)	469	623	934	SFC

The SR instruments are broadband sensors which simultaneously detect both visible (.5 to .7 μm) and IR window (10 to 12 μm) radiation. Since the NOAA spacecraft are sun-synchronous polar-orbiting satellites, simultaneous IR and visible measurements are available once per day at 0900 to 1000 local time for mid-latitudes in the Northern Hemisphere. Details of the scanning radiometer data archive have been described by Conlan (1973) and by Bunting and Conover (1976 a). Horizontal resolution of the archived SR data is about 10x10 km for both visible and IR.

The archives of visible data are normalized for solar zenith angle. However, inconsistencies in brightness are often noted at the swath edges between satellite passes. An attempt was made to reduce these irregularities by implementing the bi-directional reflectance model of Sikula and Vonder Haar (1972). Further details of the application are described in a technical report (Bunting and Conover, 1976 a). Observations in the IR array are less sensitive to viewing geometry and have not been normalized. The archive for IR includes a small correction for limb darkening due to water vapor absorption.

2.2 Aircraft Data

A series of simultaneous measurements of clouds by satellites and aircraft began in January 1974. At the approximate time of the satellite pass, an aircraft equipped with cloud physics instrumentation descended from 10 km altitude in a spiral of diameter 35 km at a descent rate of 0.3 km min^{-1} (1000 ft min^{-1}) to 0.3 km or as low as air traffic control would permit. A variety of probes was available, including a "snow stick" for visual identification of crystal habit and size, J-W liquid water sensor, continuous formvar replicator, cloud scene cameras, and Particle Measuring System 1-D spectrometers. A flight director observed the altitudes of cloud tops and bases, estimated cloud tops when clouds were above the maximum ceiling of the aircraft, estimated the fractional coverage of cloud layers, noted optical effects such as halos, and described particles intercepted by the snow stick. Supporting data included raingauge records, radar PPI scope photographs, GEOS satellite imagery, and temperatures from nearby radiosondes. The aircraft information was used to estimate cloud mass as a function of altitude averaged over a horizontal area of about 70x70 km. The horizontal area for cloud mass estimate was matched to a set of VTPR measurements.

The problem of matching the satellite and aircraft measurements is compounded by the fact that the satellite measurements are sensitive to clouds at all altitudes, but are recorded over a large horizontal scale in only 10 seconds or less. If the aircraft loiters at one altitude to get a better estimate of cloud mass, clouds at a lower altitude may advect or change before the aircraft descends to sample them. The sounding schedule was therefore a compromise so that a sounding could be completed in about 30 minutes. In some instances cloud layers were sampled for periods shorter than optimum. In all cases, the highest clouds were sampled closest to the satellite pass time. Due to the requirement for rapid sampling and the fact that aircraft instruments occasionally malfunctioned, cloud mass profiles were not determined strictly from particle counts on instruments. All data, including surface radar and rainfall data, were carefully integrated to generate a profile that was considered the best possible estimate over the entire 70x70 km square at the time of satellite observation.

3. RESULTS

3.1 Cloud Altitude and Transmissivity from IR Sounder Radiances

A method of estimating cloud altitude and transmissivity from IR sounder radiances has been described by Bunting and Conover (1974). The ordinary application of the sounder is an inversion of the radiances for clear or partly cloudy areas to estimate the vertical temperature profile. However, cloud altitude and transmissivity can be estimated from these observed radiances if the temperature profile is known. For a particular sounder channel, the radiance, I, observed by the satellite can be estimated from:

$$I = (B_S \tau_A + \int_S^C B_A \, d\tau) \, \tau_C + (B_C \tau_A)(1 - \tau_C) + \int_C^{\infty} B_A \, d\tau \qquad (1)$$

where B is the Planck radiance (a function of temperature and wavenumber), S stands for surface, C for cloud, A for air. τ_A is the transmissivity of air between a pressure level and the satellite (a function of wavenumber), and τ_C is the cloud transmissivity.

For cases when clouds were viewed by VTPR instruments τ_A was calculated at 40 levels from the surface to 200 mb. Equation (1) was applied to the four bands listed in Table 1 for 39 cloud altitudes and ten cloud transmissivities between 0.0 and 0.9. The calculated radiances were compared with the satellite observed radiances allowing for an uncertainty of $\pm$ 2.0 $mWm^{-2}sr^{-1}$ cm, which is about 2 to 5% of the radiance. Model clouds were sought which satisfied all four spectral regions. If none were found within the limits of $\pm$ 2.0, the limits were increased to $\pm$ 3.0, $\pm$ 4.0, etc. If the permitted model clouds varied in transmissivity, the clouds with the lowest transmissivity were chosen. If no clouds were found with transmissivities of 0.1 or 0.0, an uncertainty of $\pm$ 1.0 was attempted. This procedure was established by trial and error and found to give good estimates of cloud altitudes for cirrus clouds without overestimating the altitudes of lower clouds.

A comparison of observed cloud top altitudes to altitudes predicted by the 4 band overlap is given in Figure 1. Observations match the predictions for both high and low cloud tops, with the exception of some cases of cirrus above middle cloud. Cases of low clouds, middle clouds and thick cloud systems without isolated cirrus, as well as cases of cirrus alone or above low cloud, were adequately predicted by the four band overlap model. The apparent underestimate of cloud tops for some cases with cirrus above middle clouds is a limitation of the application of a one-layer cloud model to multilayer situations. The difference between the ground radiance, which appears in Equation (1), and the radiance of the middle level cloud, which does not, is great enough so that thin layers of cirrus above middle level clouds can go undetected. For these cases, the satellite cloud top is a good estimate of the middle level clouds.

In Figure (2), cloud tops for band 8 alone (12.0 μm) are compared with aircraft observations. The clouds are assumed to have a transmissivity of 0.0. In Figure (2), when observed tops are high, the window measurement often underestimates them by a substantial altitude. The four-band estimates of altitude for cirrus alone or above low cloud in Fig. 1 are far superior to the corresponding estimates in Fig. 2 for the window band only. The four-band estimates of cirrus above middle clouds are also somewhat improved. Estimates of altitude for cases with no isolated cirrus are quite good for both the four-band and the one-band models. These clouds have transmissivities close to 0. The four-band overlap model provides an estimate of cloud transmissivity as well as altitude. Estimates of cloud transmissivity can be summarized as follows: (a) all estimates of transmissivity for 21 "no isolated cirrus" cases

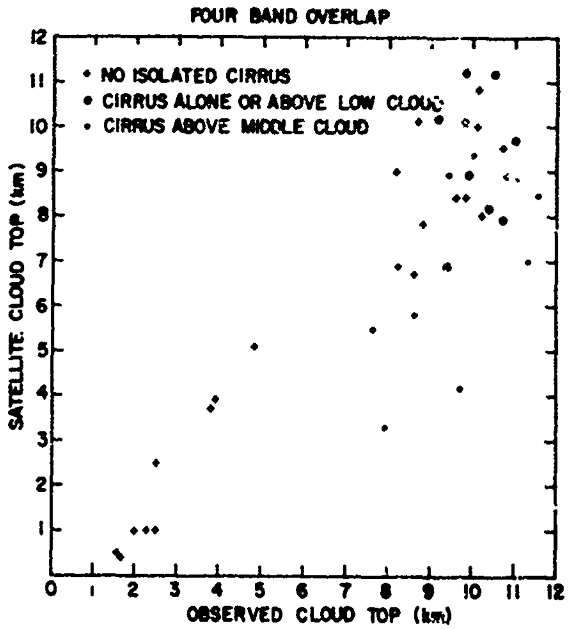

Figure 1. Observed cloud tops compared to tops estimated by an overlap of four VTPR bands on NOAA satellites.

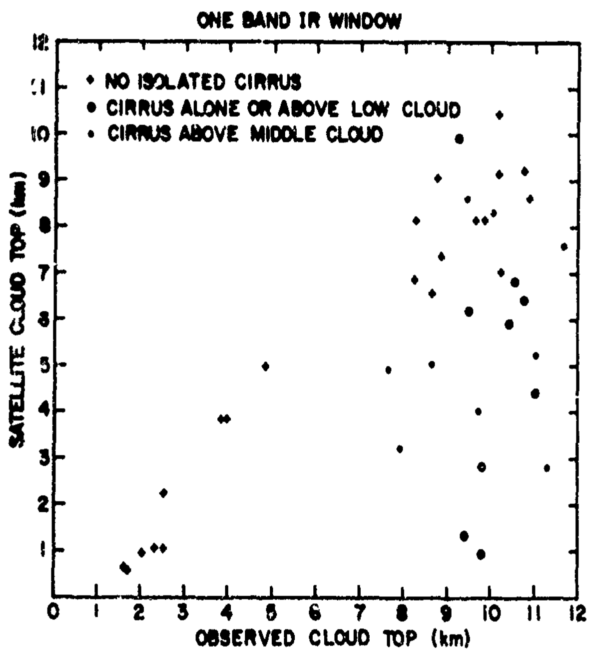

Figure 2. Observed cloud tops compared to tops estimated from band 8 only, the IR window band on NOAA VTPR instruments.

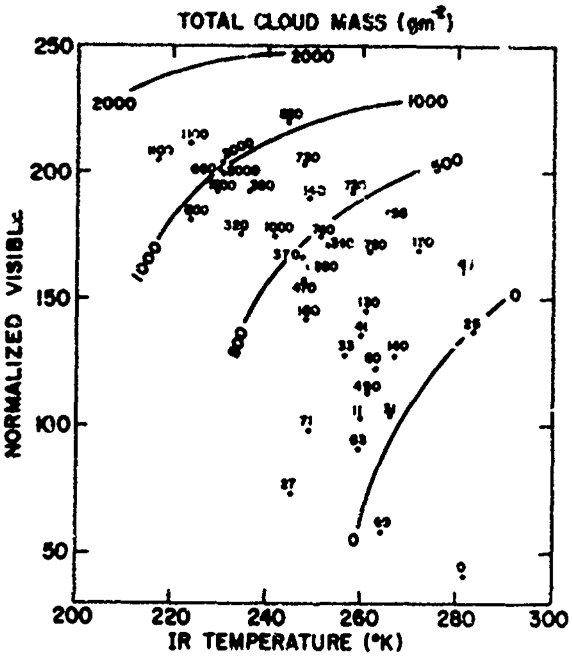

Figure 3. Simultaneous observations of total cloud mass by aircraft, and cloud visible and IR radiation from NOAA satellite Scanning Radiometers. The cloud mass is the total of both liquid and ice content integrated over altitude. The solid curves are solutions of Eq. (2).

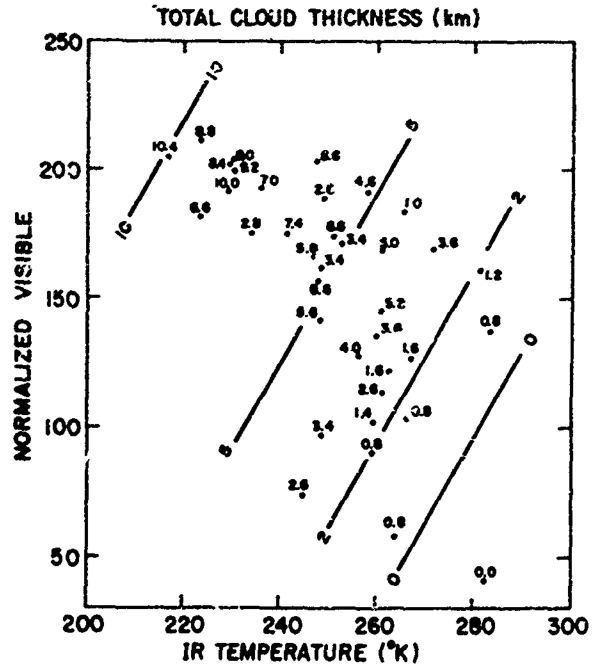

Figure 5. Simultaneous observations of total cloud thickness by aircraft, and cloud visible and IR radiation from NOAA satellite Scanning Radiometers. The lines are solutions of Eq. (3).

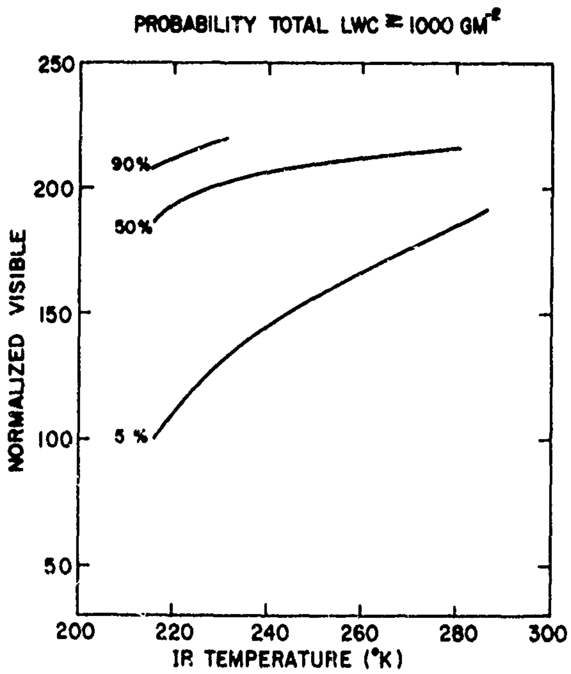

Figure 4. The probability that total cloud mass exceeds 1000 gm^{-2}, based on application of a model by Gringorten (1976) to the data in Fig. (3).

were either 0.1 or 0.0; (b) Estimates for 9 "cirrus" alone or above low cloud" cases ranged from 0.9 to 0.2 except for one case of 0.0 (which case was observed to have over three times as much cloud mass as any other case); (c) Estimates for 6 of 9 "cirrus above middle cloud" cases were either 0.1 or 0.0. These cases of suspiciously high transmissivity also underestimated cloud altitude as discussed earlier.

3.2 Cloud Mass and Thickness from IR and Visible Measurements

Figure (3) relates total cloud mass, the integral of cloud mass density over all altitudes, to visible and IR satellite measurements taken by the Scanning Radiometers. The scale of normalized visible measurements ranges from 50 to 254, and is directly proportional to luminance in foot lamberts (Conlan, 1973). Infrared measurements ($\overline{IR}$) are given as degrees Kelvin over a range of 200 to 300. The visible, IR, and cloud mass data are all averaged over a horizontal scale of about 70x70 km. Figure 3 demonstrates that simultaneous measurements were obtained for a considerable range of both satellite and aircraft data. The data in Fig. (3) were presented earlier by Bunting and Conover (1976 b), the satellite measurements have not changed, but estimates of cloud mass have been edited and improved, and one case has been added.

The curves on Figure (3) are solutions of the following equation:

$$LWC = \frac{178300}{(\overline{IR} - 125.6)} + \frac{84510}{(285.1 - \overline{B_N})} - 1709 \quad (2)$$

where $\overline{B_N}$ is the mean normalized brightness from the visible measurements, $\overline{IR}$ is the mean temperature observed by satellite in degrees Kelvin, and LWC is total ice and water cloud mass in gm^{-2}. The constants were determined by first linearizing both IR and visible measurements separately with respect to LWC and then applying multiple regression to the linearized quantities. The standard error of estimate for the 38 cases is 327 gm^{-2}, and the correlation coefficient is 0.77. When predictions of total water content are less than zero they are arbitrarily increased to zero.

A probability model by Gringorten (1976) was applied to the data in Fig. (3), in order to establish the probabilities for which a threshold of cloud mass would be exceeded as a function of cloud temperature and brightness. Figure (4) has the results for a cloud mass threshold of 1000 gm^{-2}.

An observation of cloud thickness is available for each observation of cloud mass. The total cloud thickness is plotted in Fig. (5) in relation to cloud temperature and brightness. The total cloud thickness is simply the sum of geometric thicknesses of all cloud layers. The lines in Fig. (5) are solutions of the equation:

$$\Delta H = -0.1025\ \overline{IR} + 0.0310\ \overline{B}_N + 25.73 \qquad (3)$$

where ΔH is total cloud thickness in km, and $\overline{IR}$ and $\overline{B}_N$ are defined as for equation (2). When $\overline{IR}$ and $\overline{B}_N$ were linearized with respect to ΔH, the resulting quantities were not significantly better predictors of ΔH; therefore, multiple regression on the ordinary variables is given as equation (3). The standard error of estimate for the 38 cases is 1.6 km, and the correlation coefficient is 0.86. When predictions of total cloud thickness are less than zero they are arbitrarily increased to zero.

The observations of Figures (3) and (5) clearly confirm a very simple physical hypothesis: clouds which appear coldest in the IR and brightest in the visible have the greatest total mass and vertical thickness. This paper tests the hypothesis over a wide range of cloud conditions and satellite measurements. Moreover, there are a number of ex post facto reasons for such results: (a) For clouds opaque to IR, warm cloud temperatures correspond to low cloud tops, and statistically to low cloud mass and thickness; (b) For clouds semi-transparent to IR, warm observed cloud temperatures do not correspond to low cloud tops but do correspond by observation and theory to low cloud mass and thickness; (c) For arbitrarily fixed particle size distributions, calculations for the reflection of sunlight predict that the brighter the cloud, the greater the cloud mass and thickness; (d) Sunlight is expected to be less attenuated by atmospheric scattering and absorption in the path from the sun to cloud to satellite when the cloud has great thickness and mass, so that these clouds should appear bright; (e) Convective clouds tend to grow wider as they grow thicker, so that less sunlight is scattered out the sides of the clouds and more sunlight out the top.

5. FUTURE WORK

There is room for improvement in several areas. First of all, models for normalization of reflected sunlight to standard viewing geometry are expected to improve in the near future as results become available from the Earth Radiation Budget Experiment on the Nimbus 6 satellite. Second, methods of estimating average cloud mass density over areas from aircraft, radars, and lidars are also expected to undergo gradual improvement. Third, our own data bank is being expanded to include cases of heavier weather in convective systems. The highest cases of cloud mass were 2000 gm^{-2}. Considerably higher values for total cloud mass are expected in the tropics, or in temperate latitudes in summer. Data published here were recorded in stratiform cloud systems during winter and spring. Finally, areas with snow cover may appear sufficiently bright in the visible, and cold in the IR to be misinterpreted as areas of cloud cover. These "false alarms" can be reduced by converting temperature to altitude and using a new regression estimate for LWC. Ratios of narrow band measurements of reflected sunlight at .76, 1.6, and 2.1 µm may not only correct this snow problem for future satellite instruments, but also distinguish among ice clouds, water clouds, and snow (Alishouse, 1976).

Sun-synchronous passes by satellites provide data at a given location only twice per day; however, there is no reason why the technique discussed in this paper could not be applied to geostationary satellites thereby permitting hourly estimates of LWC.

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